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COLLINEAR-TRACK ALTIMETRY IN THE GULF OF MEXICO FROM SEASAT: ME--ETC(U)
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Collinear-Track Altimetry in the Gulf of Mexico from SEASAT: Measurements, Models and Surface Truth

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ABSTRACT

From 17 September to 10 October 1978 SEASAT made collinear passes over the Gulf of Mexico. Altimeter data for eight, three-day repeat passes over the eastern Gulf were examined using an arc-segment fitting technique to determine the mesoscale temporal variability of the sea surface. The pattern of sea height variability was then compared with sea height data generated by a numerical model of the Gulf (Hurlburt and Thompson, 1980) from the simulation of a complete cycle of Loop Current intrusion and shedding of an anticyclonic eddy. The model data was found to match that from the SEASAT altimeter when an anticyclonic eddy separated from the Loop Current and the Loop began to repenetrate into the eastern Gulf. Analysis of sparse ground truth data from ship-of-opportunity XBT's, satellite infrared imagery of the Loop Current boundary, and synthetic aperture radar (SAR) imagery, also from SEASAT, tend to confirm the circulation patterns deduced from the altimeter data and the numerical model.

1.0 Introduction

The absolute dynamic topography (height of the sea surface relative to the geoid) due to ocean currents is detectable using satellite-borne radar altimetry in conjunction with accurate knowledge of the marine geoid. For example, Cheney and Marsh (1981a) used SEASAT altimeter data and the best available geoid model of the Western Atlantic to determine the height of the sea surface, the position of the Gulf Stream and cyclonic and anticyclonic rings near the Stream, and the component of the surface geostrophic velocity perpendicular to the satellite ground tracks. Bernstein et al.(1982) have compared the dynamic height changes obtained from repeat tracks of SEASAT altimeter data with data obtained from aircraft AXBT's across the Kuroshio Extension. The two data sets show good agreement, generally within 10 cm, for surface height changes due to the time-varying geostrophic current. Data from the less accurate GEOS-3 altimeter also have been used to examine the variability of the sea surface in the vicinity of the Gulf Stream (Huang et al., 1978; Cheney and Marsh, 1981b).

This paper is concerned with the application of SEASAT altimeter data to the study of ocean dynamics in the Gulf of Mexico. The Loop Current in the eastern Gulf is of particular interest since it has a transport of approximately 30 X 10^6 m^3s^{-1} and eventually becomes a principal component of the Gulf Stream. Entering the Gulf through the Yucatan Strait, the Loop Current traces an anti-cyclonic path which at times nearly extends to the Mississippi Delta before turning southward and exiting through the Florida Straits. Maximum geostrophic surface currents in the Loop can be greater than 150 cm sec^{-1} and the dynamic height across the stream sometimes exceeds 75 cm. Large anticyclonic eddies (also termed "rings") have been observed to break off from the Loop Current following these intrusions. The major eddies typically have diameters of about

360 km and translate into the western Gulf with a mean speed of 2.4 cm sec^{-1} (Elliott, 1979).

For some time it was believed that the Loop Current penetrated into the Gulf during spring and summer, shed a large anticyclonic eddy during late summer and fall and exhibited minimum penetration in the winter (Leipper, 1970; Cochrane, 1972). Molinari et al.(1977) showed this view principally reflected a bias in the sparse data set. New oceanographic data and satellite information cast doubt on the hypothesis that the Loop Current exhibits an annual cycle. For example, a statistical analysis by Molinari (1980) showed a range of shedding periods of eight to fifteen months while Elliott (1979) discovered that during a single year three (and possibly four) rings separated from the Loop Current. Results from a numerical model of the Gulf of Mexico by Hurlburt and Thompson (1980; henceforth referred to as HTa) demonstrated that with a realistic constant inflow transport the mean period between major eddy break-off was about ten months.

Although available geoid models for the Gulf of Mexico are not as accurate nor as highly resolved as those for the western North Atlantic, estimates of the temporal variability of the height of the sea surface can still be made along precisely repeating ground tracks since the geoid contribution to the sea surface height is time-invariant. Meandering currents, translating eddies, and other mesoscale features exhibiting significant temporal variability are detectable using this technique.

From Sept. 17 to Oct. 10, 1978, SEASAT made a sequence of eight collinear passes over the Gulf of Mexico. In Fig. 1 ground tracks have been superimposed on a near-synoptic map of the depth of the 22^{o} isotherm obtained by Leipper (1970) from data collected during August 1966. The Loop Current and a large anticyclonic eddy about to break off from the main flow (Elliott, 1979) are clearly evident. We emphasize that Fig. 1 depicts the configuration of the Loop Current nearly 12 years prior to the SEASAT mission and does not necessarily correspond to

oceanographic conditions present during September and October 1978. Unfortunately, sufficient ground truth data was not available during SEASAT to undertake a detailed synoptic analysis such as that made by Leipper. However, there is evidence, discussed below, indicating that an eddy did separate from the Loop Current just prior to the SEASAT mission. We have used Leipper's map to illustrate this oceanographic pattern.

SEASAT altimeter data from the collinear passes have been used to compute relative temporal changes in the dynamic sea surface topography from pass to pass. Results from these calculations are examined for consistency with the known mesoscale dynamics of the Gulf of Mexico. A numerical model of the Gulf of Mexico is used to generate a set of synthetic altimeter data for ground tracks similar to those actually traced out by SEASAT. The resulting data set calculated serially over an entire eddy shedding cycle is compared to the SEASAT results. During the period after the Loop Current reaches maximum penetration, sheds an anticyclonic eddy, and begins to repenetrate into the Gulf, the model and the altimeter data are similar. Limited in situ data in the form of expendable bathythermographs (XBT's) from ships of opportunity in the Gulf are used as surface truth to evaluate the SEASAT altimeter data and the model results. Unfortunately, a shallow surface layer of warm water covers the Gulf from June to early October so no surface thermal signature of the Loop Current is detectable in infrared satellite imagery during this period. However, 428 GOES observations from February 1976 to February 1981 have been used to determine the position of the Loop Current boundary along a line from Cape San Antonio (extreme western Cuba) to the Mississippi Delta (Maul et al, 1978). A Fourier analysis of this data, in conjunction with the GOES IR images from 31 May and 21 October which bracket the SEASAT mission, provide some estimate of the position of the Loop Current during the collinear passes. The synthetic aperture

radar (SAR) onboard SEASAT provided additional collaborative information on Loop Current position. The altimeter data, model results, and ground data are combined to produce a consistent description of the circulation in the eastern Gulf during the late summer and early fall of 1978.

2. SEASAT Altimeter Data

The SEASAT altimeter directly measured the radial distance from the satellite to the sea surface using travel times for short (3ns) microwave (13.5 GHz) pulses measured approximately 1000 times per second. Data was compressed on the spacecraft into a 10 point per second set. The footprint of the microwave pulse, a function of sea state, was roughly 2 km in diameter for 1-2m significant wave heights.

The raw data must be corrected for contributions from a number of error sources (for details, see the Report of the TOPEX Science Working Group, 1981 or Tapley, et al., 1982). Corrections for height estimation errors due to instrument effects, tropospheric (both wet and dry) components and ionospheric effects have been made. Sea state bias errors are uncorrected but are not significant for these tracks. Solid earth and ocean tidal signatures have been removed from the altimeter data by the use of global models. Inaccuracies in orbit determination introduce a long wavelength error which is manifest as an unknown tilt plus an unknown bias. Using the technique of arc segment fitting (Gordon and Baker, 1980; Cheney and Marsh, 1981b) the long wavelength errors in the radial component of the ephemeris can be removed. The procedure involves four steps. First, errors in the altimeter-measured distance between the ocean's surface and the altimeter introduced by the error sources discussed above are corrected. Then, using the precision orbit determination data, sea surface height relative to a reference ellipsoid is calculated. Third, the average height for all repeat tracks is removed from each of the repeat-track arc segments. Changes in the average height from point to point are largely due to changes in the geoid along the track. Finally, each track is fitted to have zero bias and no tilt along the arc segment. This last step removes most of the long wavelength error in the orbit determination. Now the data set is suitable for the analysis of mesoscale variability.

Applying the arc segment fitting technique, we have plotted the data from each collinear pass for Track 2 (Fig. 2) and Track 3 (Fig. 3) over the Gulf. Although the arc segments are relatively short, mesoscale features are clearly not lost. Note the large contribution to the sea surface height due to the geoid in Fig. 2a and 3a. Along Track 2 a transient feature is evident near 85.75°W on rev 1175 (Fig. 2c) which progresses eastward to 84.6°W by rev 1476, twenty-one days later. The maximum sea height change at a given point along the track is 65 cm and the maximum rms amplitude is about 15 cm at 84.9°W. The maximum rms variability of the cross track surface geostrophic current is obtained from $|v| = \frac{g}{f} \left|\frac{\partial\zeta}{\partial n}\right|$, where ζ is the rms variability of the sea height, f is the Coriolis parameter and n is the cross track direction. During the period Sept. 17 to Oct. 8 this value was about 40 cm sec^{-1} at 84.7°W averaged over 50 km. Along Track 3, a feature 100 km in width centered at 90°W yields a maximum of 9 cm rms amplitude and a total sea height change of 30 cm. The rms variability of the cross track geostrophic current is about 20 cm sec^{-1}. Note also the gradual drop in sea surface height at 90W from the beginning of the period to the end of the period.

3. Numerical Model Results

A hierarchy of research models (two-layer, barotropic, and equivalent barotropic) of the Gulf of Mexico have been developed by Hurlburt and Thompson (1980, 1982; HTz and HTb, respectively). These models have been used successfully to investigate the dynamics of the Gulf, particularly the northward penetration of the Loop Current and the eddy-shedding process. Typically these primitive equation hydrodynamic models were spun up from rest and integrated for 3-5 years to statistical equilibrium, forced by prescribed inflow through the Yucatan Strait and compensating outflow through the Florida Straits. We have used their two-layer model with idealized topography in a rectangular domain and tilted 20^0 with respect to latitude (See Fig. 4). The model parameters were selected to be as realistic as possible within the two-layer framework and are exactly those from the "standard" case described by HTa except that the horizontal eddy viscosity is 3×10^6 cm^2 sec^{-1}, the lower layer transport is 5×10^6 m^3 sec^{-1} and a "parabola-squared" transport profile is used across the inflow port. The lower value for the horizontal eddy viscosity was used in order to make the simulation as realistic as possible. No tidal components or spatial variations in gravity (to reflect geoid variations) were included.

The model was spun-up from rest for three years, at which time the Loop Current began to penetrate into the Gulf and shed anticyclonic eddies in a regular fashion. An imaginary altimeter was then "flown" over the model along SEASAT ground tracks for an entire model year. The sea surface height data from these tracks were examined over time periods comparable to the duration of the SEASAT repeat tracks, i.e. 21 days. During only one time period in the year did the model sea heights match patterns from the SEASAT altimeter. This period began after the Loop Current had penetrated into the Gulf and shed an

anticyclonic eddy. Fig. 4a,b shows two instantaneous pictures of the PHA (pycnocline height anomaly) at the beginning and ending of the period for which the model altimeter data and the observations agree. The PHA is the deviation of the interface between the two layers from an initially horizontal surface. Downward deviations are positive. We have chosen contours of PHA rather than sea surface height to more closely correspond to Leipper's map of the depth of the 22^{o}C isotherm in Fig. 1. Fig. 4c shows the rms variability in the sea surface height during the period. In the deep water of the model a 10 m depression in PHA roughly corresponds to a 3 cm doming of the sea surface.

The shedding process, as described by HTa and HTb, is dominated by a barotropic instability of the Loop Current. The growth rate of the instability yields a time scale that is short compared to the time required for the Loop to penetrate into the Gulf. Near the end of the period the Loop Current repenetrates into the Gulf, shifts its axis from northwest to northeast and flows southwards along the margin of the continental slope on the west Florida Shelf. The large anticyclone which breaks off from the Loop drifts slowly southwestward during this period.

Fig. 5a,b corresponds to Fig. 2c,d and represents synthetic altimeter data from the Gulf model analyzed precisely like the SEASAT data, including the removal of a tilt and bias (which are negligible) from each track. Note that in both the model results and the observations the position and the amplitude of the rms variability is similar. The maximum in both the model data and the observations occurs at 84.9^{o}W. The maximum value of rms variability in the model data is about 12 cm compared with about 15 cm in the altimeter data. The width scale of the peak is somewhat larger in the altimeter data than in the model. In both data sets there is a rise in variability as one moves toward the continental shelf east of 84^{o}W.

Along Track 3 the model and the observations are not in general agreement with respect to amplitude. The model variability along Track 3 is only about 10% of that found in the observations. However, a relative maximum is found at 90W in both the model results and the SEASAT data. Several explanations for the discrepancies in the model data are possible. First, the actual anticyclonic eddy may have moved more rapidly along this track than indicated by the model. Faster translation speeds would lead to larger rms variability during the 21-day period. The anticyclonic eddy which drifts across the ground track in the model moves westward at about 2.9 cm sec^{-1}. This is slower than the speed of movement of eddies from the reduced gravity experiments (typically about 3.2 cm sec^{-1}) reported by HTa and is considerably slower than the speeds reported by HTb for two-layer experiments in which baroclinic instability as well as barotropic instability was important. In those experiments the eddie propagated westward soon after breakoff at speeds near 10 cm sec^{-1}, a speed more appropriate to the external rather than the internal Rossby wave speed. Occasional rapid westward movement of eddies also has been observed by satellites using remotely-sensed surface temperature measurements. The ground truth data in this instance is not sufficient to determine either the extent of baroclinic instability existing within the eddy or its rate of westward movement. However, there is some evidence to support a higher translation speed in Fig. 3c and in the ground truth measurements discussed in Section 4. In Fig. 3c the relative value of the sea heights near 90W <u>decreases</u> with each successive pass, suggesting that the center of the eddy was west of the ground track at the beginning of the collinear passes. To emphasize the importance of the translation speed of the eddy in determining rms variability, consider Fig. 4c which shows the rms variability of the sea surface height during the 21-day period. TRACK 2 crosses just northwest of the maximum rms variability while TRACK 3 passes through the

relative minimum in variability produced by the moving anticyclone. Clearly, only a small change in speed of translation or eddy position at the beginning of the repeat track passes would produce a rms variability along TRACK 3 more in agreement with the observations.

A second explanation for the lower rms variability along TRACK 3 is that the real anticyclone may have been more intense or more radially asymmetric than shown by the model. In that case a larger sea height gradient would translate across the ground track in a given period - again yielding greater rms variability. Asymmetric eddies have been observed to break off from the Loop Current, but there is little observational support for the existence of eddies significantly more intense than those produced by the model.

4. The Ground-Truth Data

The altimeter data and the model results have led us to propose that an anticyclonic eddy must have detached from the Loop Current just prior to the SEASAT collinear overflights. Furthermore, a partial repenetration of the Loop Current towards the northeast to the continental slope of the West Florida Shelf must have occurred by the end of the period. It remains to determine if this hypothesis is justified by the scarce *in situ* oceanographic data.

Unfortunately, no dedicated oceanographic experiment was undertaken in the Gulf of Mexico during SEASAT. Fig. 7 shows the available XBT data from the Gulf of Mexico during August 1978 and also includes information on the Loop Current boundary from the last available satellite IR image obtained before summer insolation and atmospheric humidity obscured the surface thermal contrast. Neither the XBT data nor the GOES data were precisely coincident in space or time with the SEASAT collinear passes. The GOES data were analyzed using the image sequence technique described by Maul et al. (1978). The current boundary determined by satellite is typically 10-15 km shoreward of the 22°C isotherm at 100 m. On May 31 the Loop Current had penetrated far north into the Gulf and was about to shed an anticyclonic eddy. The sausage shaped frontal region to the east near Florida is probably not part of the Loop Current but is an isolated warm water patch trapped on the Florida Shelf. Its origin is unknown.

By 12-13 August, six weeks later, the 22°C isotherm was observed to be deeper than 150 m at 25°N, 90°W indicating the presence of an eddy or the Loop Current. From the single XBT line we cannot be certain that an isolated eddy was traversed. However, also shown in Fig. 7 is the location of light and dark bands or "streaks" detected on July 24 by the synthetic aperature radar (SAR) on SEASAT. These streaks are similar to those observed by Hayes (1981) along the Gulf Stream boundary and by Lichy et al. (1981) in warm core Gulf Stream rings. Fig. 8 shows the actual optically-processed SAR image for the boxed area of Fig. 7. Although the process which generates these streaks is not well understood, it is most likely associated

with the interaction of small gravity waves and a strong mean current. It is likely that the streaks mark the boundary between the Loop Current and the ambient Gulf water. Since the Loop Current is bending anticyclonically to the east on July 24, it is very unlikely that during a three-week period it could recurve to the west and be detected in the XBT transect of 12-13 August. Based on this information and our knowledge of the time and space scales of shed anticyclones in the Gulf we conclude that a detached eddy did exist near 90°W during August 1978.

Fig. 9 provides XBT data for 15-17 September, 21 September and 14 October and two SAR swaths parallel to the collinear subsatellite ground tracks. Near 27°N, 87°W no clear eddy signature was observed, although the 75 m contour may indicate the eastern edge of a weak anticyclonic eddy. By 14 October this weak anticlone may have translated southwestward to near TRACK 3. On 11 and 20 September alternating light and dark bands ("streaks") were observed in the SAR swath perpendicular to TRACK 3. Once again these streaks probably follow the surface position of the Loop Current. This interpretation is consistent with the XBT data taken from 25.8°N, 84.8°W to 28.8°N, 88.3°W during 15-17 September. The Loop Current did not extend either eastward or northward to this line. On 11 and 20 September curved streaks were noted roughly parallel to the SAR swath from the western tip of Cuba to about 24°N. This may be the signature of the eastern edge of the Loop Current. Because the sea surface temperature at this time was nearly uniform, the SAR streaks were not due to changes in sea state attributable to corresponding variations in boundary layer stability and wind drag as has been suggested by Weissman and Thompson (1976) in the Gulf Stream.

Fig. 10 shows the first fall GOES image (21 October) to delineate the Loop Current boundary. The Loop Current has penetrated to the north and to the east, with its eastern flank set against the continental slope along the west Florida shelf. XBT's taken on 26-27 October suggest that the anticyclonic eddy near

$15^{o}N$ and $91^{o}W$ observed on 14 October has continued to drift southwestward. The Loop Current crosses the XBT line of 20-21 November at about 24.5N and there is no evidence for a shed eddy further north along the line toward the Mississippi Delta.

A useful way to synthesize these diverse observations is shown in Fig. 11. Between February 1976 and February 1981 428 GOES observations of the Gulf Loop Current boundary were made using the Cape San Antonio, Cuba - Mississippi Delta line as a "wave-staff." These 428 positions form a randomly spaced (fall, winter, spring), gappy (summer) time series which has been analyzed as outlined by Maul et al.(1978). Dominant peaks in the least squares spectrum of the five year record are at 147, 287, 206, and 65 days with a notable spectral gap at 365 days. Subtracting these four components and the linear trend from the time series reduces the variance about the mean from $\pm$ 130 km to $\pm$ 78 km. The calculated distances along the "wave-staff" for a similar analysis using the nine most dominant periods (standard deviation for five years $\pm$ 63 km) is indicated in Fig. 11. Included are the GOES sequence analysis from day 800 through 1100 and the 31 May and 21 October locations from Fig. 7 and Fig. 9, respectively. Note the multi-valued distances on 31 May and the location of the SEASAT SAR "streaks."

We propose that following the maximum penetration of the Loop Current around 1 May, an eddy began to separate from the Loop Current. By early June a major 200-300 km diameter anticyclonic eddy completely broke away from the Loop Current and drifted southwestward. About 140 days later the Loop Current again had reached maximum penetration and shed another eddy, this one weaker and probably smaller than the previous one. This eddy drifted southwestward and appeared in the 14 October and 26-27 October XBT data near TRACK 3. Meanwhile, the Loop Current repenetrated into the Gulf such that by 21 October the main core of the Loop Current was as far north as $27^{o}N$. Subsequent GOES satellite imagery (not

shown) suggests that the late October northeasterly intrusion led to another separated eddy north of Cape San Antonio which did not drift westward.

5. Summary Conclusions

SEASAT collinear passes over the Gulf of Mexico were examined to determine the temporal variability in the height of the sea surface during the period 17 Sept. to 10 Oct. 1978. An arc segment fitting technique (Cheney and Marsh, 1981b) and time differencing was employed to study the rms variability of the sea height along two collinear tracks in the eastern Gulf.

A numerical model of the Gulf of Mexico (Hurlburt and Thompson, 1980) was used to simulate the penetration of the Loop Current into the Gulf and the shedding of large anticyclonic eddies from it. Sea surface heights from the model output were observed along the same collinear tracks as in the actual Gulf. An analysis of model data identical to that undertaken for SEASAT altimeter data suggested that the same pattern of sea height variability only occurred just after the Loop Current had shed an anticyclonic eddy and had begun to re-penetrate into the Gulf. However, the model underpredicted the speed of movement of the shed eddy and the rms variability of the sea height associated with it. The shed eddy drifted southwestward during the period while the eastern extension of the Loop Current flowed southward very near the continental slope of the west Florida Shelf.

Analysis of ground truth data from ship-of-opportunity XBT's, satellite infrared imagery of the Loop Current boundary, and synthetic aperture radar (SAR) imagery, also from SEASAT, provide some confirmation of the circulation patterns deduced from the altimeter data and the numerical model results for September and October 1978 in the eastern Gulf of Mexico. The ground truth data is consistent with the hypothesis that the Loop Current shed a weak anticyclonic eddy in early September which drifted southwestward as the Loop Current began to repenetrate into the eastern Gulf. This combination of altimeter data, model results, and ground truth data demonstrates that satellite altimeters can provide useful oceanographic information even without detailed knowledge of the geoid,

so long as collinear passes are repeated at a sufficiently high frequency and long wavelength uncertainty in the radial component of the orbit can be removed. Future altimetric satellites, in conjunction with an accurate marine geoid, have the potential for providing sea height information and absolute surface geostrophic velocities on a global, all-weather basis, thus providing oceanographers with the beginnings of a truly synoptic ocean monitoring system.

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FIGURE LEGENDS

Fig. 1: SEASAT collinear ground tracks over the Gulf of Mexico superimposed on a map of the topography of the 22°C isothermal surface, 4-18 August 1966 (Alaminos cruise 66-A-11) from Leipper (1970). The Loop Current and an apparent anticyclonic eddy about to separate from it are defined by the closely packed contours. The eastern Gulf may have had a somewhat similar configuration during September 1978, but with a considerably weaker anticyclonic eddy.

Fig. 2: Analysis of eight collinear altimeter profiles collected along TRACK 2 in Fig. 1 by SEASAT over the Gulf of Mexico from 17 September to 8 October 1978: (a) sea height relative to the reference ellipsoid; (b) profiles replotted after subtraction of the group mean; (c) lower: profiles after removal of orbit error through tilt and bias adjustment; upper: same profiles separated vertically by 50 cm and displayed at 3-day intervals. Revolution number is indicated for each collinear pass; (d) rms variability about the mean. The abscissa is distance along the track projected to longitude.

Fig. 3: Same as Fig. 2 but for TRACK 3.

Fig. 4: Contour plots of pycnocline height anomaly (PHA) in m at day 1272 (a) and 1293 (b) for the model simulation of the Gulf. In (c) the rms variability of the sea height over the 21-day period is contoured in 2 cm intervals. Idealized topography has been included in the rectangular domain of the numerical model (see Hurlburt and Thompson, 1980).

Fig. 5: Similar to the analysis of Fig. 2 except the altimeter is "flown" over the model sea surface along TRACK 2: (a) lower: profiles after removing the group mean plus tilt and bias adjustment. (Although there is no geoid or orbit error in the model these procedures are included to be consistent with the SEASAT analysis), upper: same profiles separated vertically by 20 cm and displayed at 3-day intervals. Day number noted for each pass. (b) rms variability about the mean.

Fig. 6: Similar to Fig. 5 but for TRACK 3.

Fig. 7: Depth of the 22°C isothermal surface along a line from the Yucatan Strait to Galveston obtained from NODC ship-of-opportunity XBT data for 12-13 August 1978. Also shown is the last surface position of the frontal boundary of the Loop Current as detected by GOES satellite infrared imagery (31 May). Location of the image from the synthetic aperture radar (SAR) shown in Fig. 8 is indicated by the rectangle.

Fig. 8: Optically processed synthetic aperture radar image from Rev. 393, July 24, 1978 for the region shown by the box in Fig. 7. The Loop Current boundary is delineated by the SAR streaks. (See Fu and Holt, 1982).

Fig. 9: Depth of the 22°C isothermal surface along XBT lines from measurements on 15-17 September, 21 September, and 14 October 1978. Also shown are the SEASAT ground tracks and the swaths mapped out by the synthetic radar.

Fig. 10: Depth of the 22°C isothermal surface along two lines taken from XBT measurements on 26-27 October and 20-21 November 1978. Also shown is the first surface position of the frontal boundary of the Loop Current detected by GOES on 21 October following the summertime loss of the surface thermal gradient.

Fig. 11: Position of the Loop Current boundary along a "wave-staff" extending from Cape San Antonio (extreme western Cuba) to the Mississippi Delta versus time in Julian days from 1 January 1976. Dots are the boundary positions obtained by the GOES sequence-analysis technique of Maul et al (1978). Multivalued distances indicate the existence of extreme Loop Current meanders or shed anticyclonic eddies. The solid line represents a nine-component Fourier recomposition (standard-deviation for five years $\pm$ 63 km) of 428 GOES observations of the Loop Current boundary which formed a randomly-spaced, gappy (in summer) time series.

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FIGURE 1

SEASAT collinear ground tracks over the Gulf of Mexico superimposed on a map of the topography of the 22^{o}C isothermal surface, 4-18 August 1966 (*Alaminos* cruise 66-A-11) from Leipper (1970). The Loop Current and an apparent anticyclonic eddy about to separate from it are defined by the closely packed contours. The eastern Gulf may have had a somewhat similar configuration during September 1978, but with a considerably weaker anticyclonic eddy.

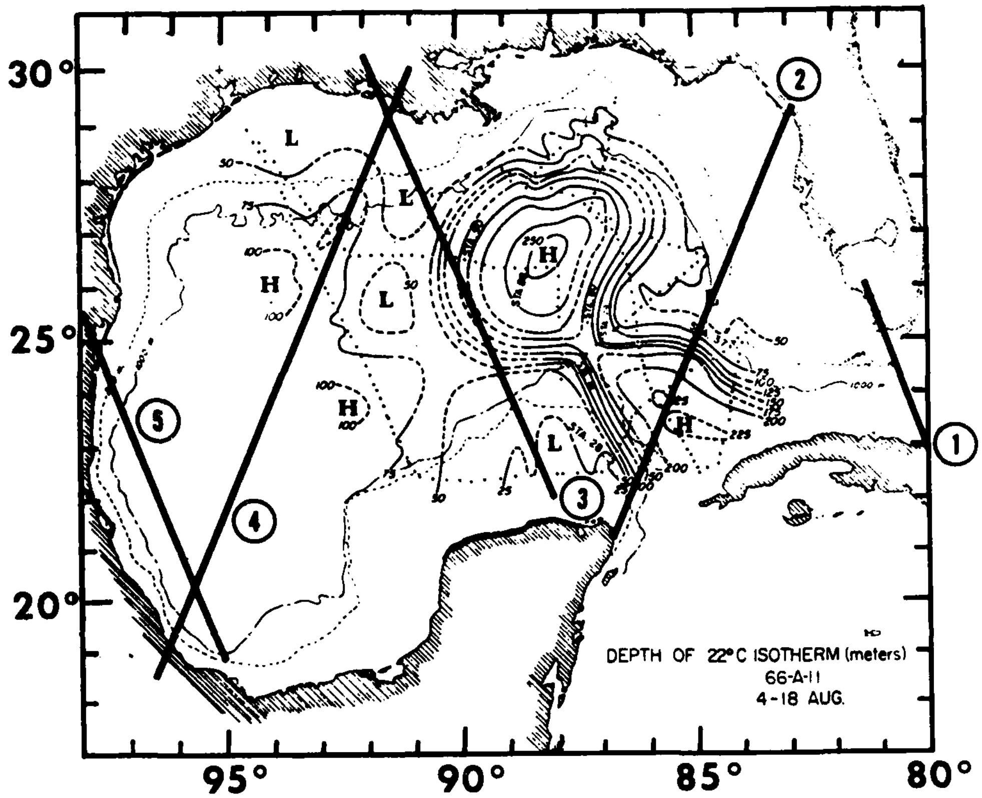
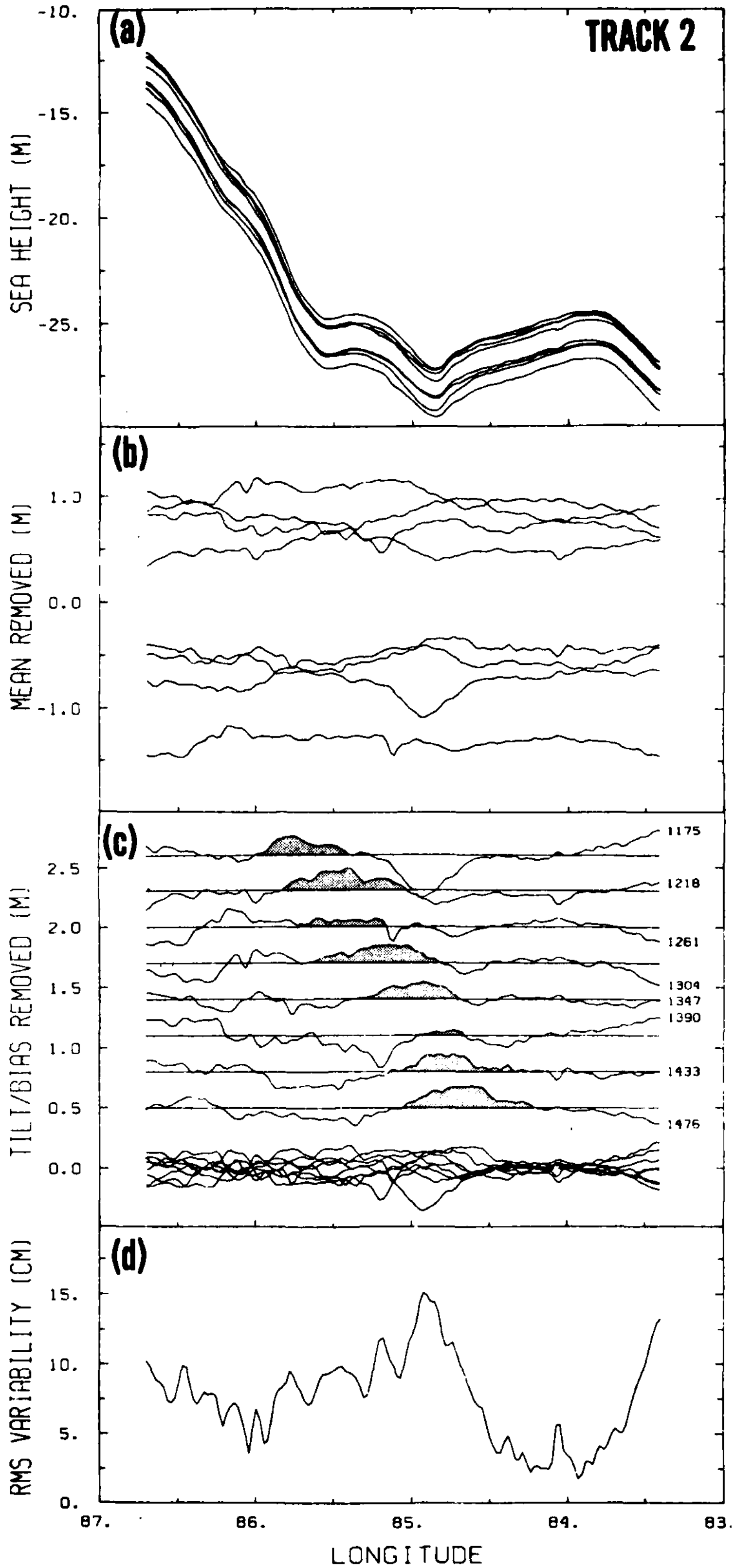

30°
25°
20°
95°
90°
85°
80°
1
2
3
4
5
L
H
DEPTH OF 22°C ISOTHERM (meters)
66-A-11
4-18 AUG.

Fig. 1

FIGURE 2

Analysis of eight collinear altimeter profiles collected along TRACK 2 in Fig. 1 by SEASAT over the Gulf of Mexico from 17 September to 8 October 1978: (a) sea height relative to the reference ellipsoid; (b) profiles replotted after subtraction of the group mean; (c) lower: profiles after removal of orbit error through tilt and bias adjustment; upper: same profiles erparated vertically by 50 cm and displayed at 3-day intervals. Revolution number is indicated for each collinear pass; (d) rms variability about the mean. The abscissa is distance along the track projected to longtitude.



TRACK 2
(a)
(b)
(c)
(d)
SEA HEIGHT (M)
-10.
-15.
-20.
-25.
MEAN REMOVED (M)
1.0
0.0
-1.0
TILT/BIAS REMOVED (M)
2.5
2.0
1.5
1.0
0.5
0.0
1175
1218
1261
1304
1347
1390
1433
1476
RMS VARIABILITY (CM)
15.
10.
5.
0.
87.
86.
85.
84.
83.
LONGITUDE

Fig. 2

FIGURE 3

Analysis of eight collinear altimeter profiles collected along TRACK 3 in Fig. 1 by SEASAT over the Gulf of Mexico from 17 September to 8 October 1978: (a) sea height relative to the reference ellipsoid; (b) profiles replotted after subtraction of the group mean; (c) lower: profiles after removal of orbit error through tilt and bias adjustment; upper: same profiles separated vertically by 50 cm and displayed at 3-day intervals. Revolution number is indicated for each collinear pass; (d) rms variability about the mean. The abscissa is distance along the track projected to longitude.

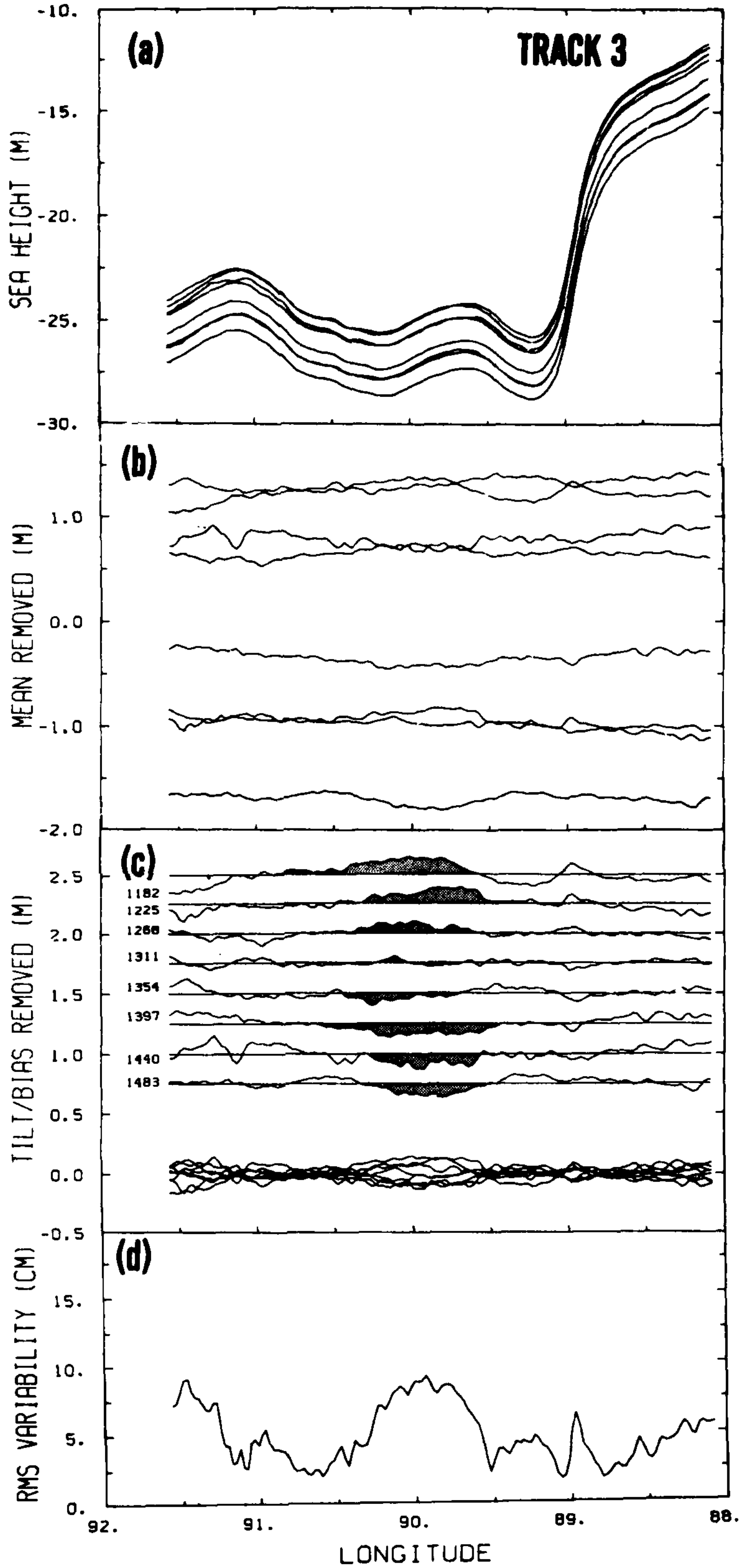

(a)
TRACK 3
SEA HEIGHT (M)
-10.
-15.
-20.
-25.
-30.
(b)
MEAN REMOVED (M)
1.0
0.0
-1.0
-2.0
(c)
TILT/BIAS REMOVED (M)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
1182
1225
1268
1311
1354
1397
1440
1483
(d)
RMS VARIABILITY (CM)
15.
10.
5.
0.
92.
91.
90.
89.
88.
LONGITUDE

Fig. 3

FIGURE 4

Contour plots of pycnocline height anomaly (PHA) in m at day 1271 (a) and 1293 (b) for the model simulation of the Gulf. In (c) the rms variability of the sea height over the 21-day period is contoured in 2 cm intervals. Idealized topography has been included in the rectangular domain of the numerical model (see Hurlburt and Thompson, 1980).

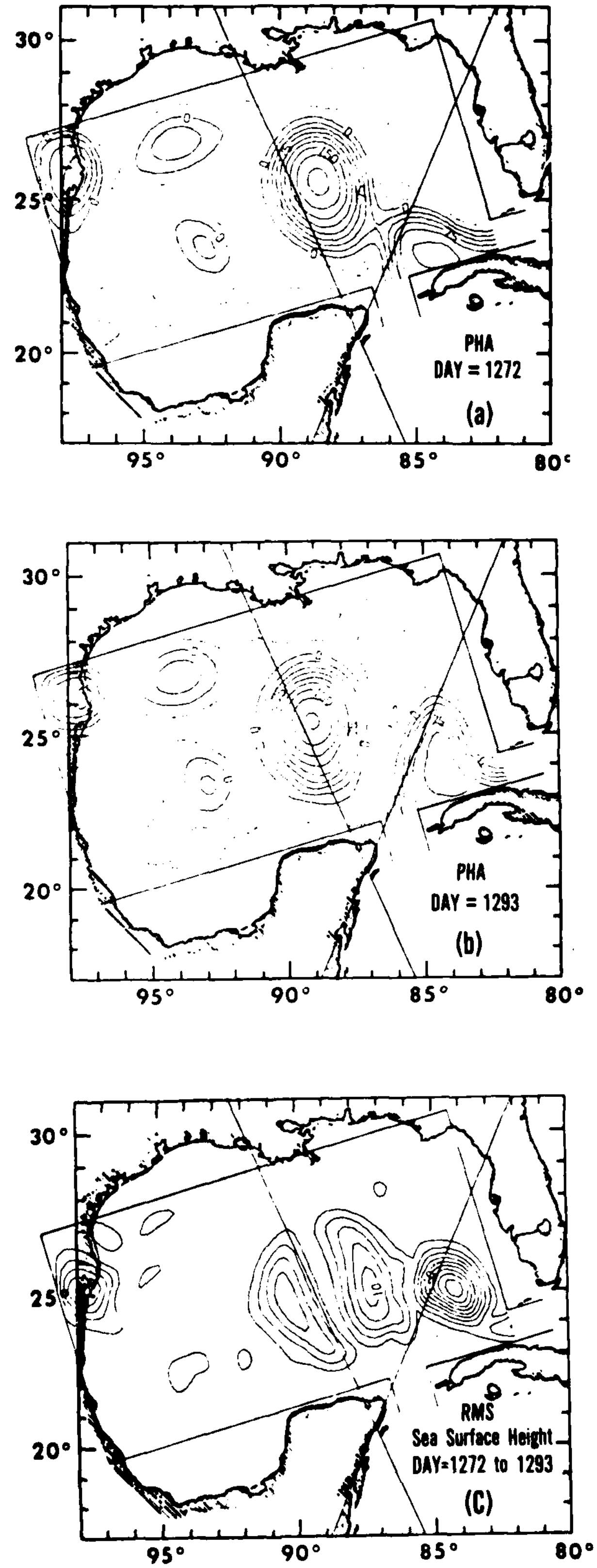

30°
25°
20°
95°
90°
85°
80°
PHA
DAY = 1272
(a)
PHA
DAY = 1293
(b)
RMS
Sea Surface Height
DAY=1272 to 1293
(C)

Fig.4

FIGURE 5

Similar to the analysis of Fig. 2 except the altimeter is "flown" over the model sea surface along TRACK 2: (a) lower: profiles after removing the group mean plus tilt and bias adjustment. (Although there is no geoid or orbit error in the model these procedures are included to be consistent with the SEASAT analysis), upper: same profiles separated vertically by 20 cm and displayed at 3-day intervals. Day number noted for each pass. (b) rms variability about the mean.

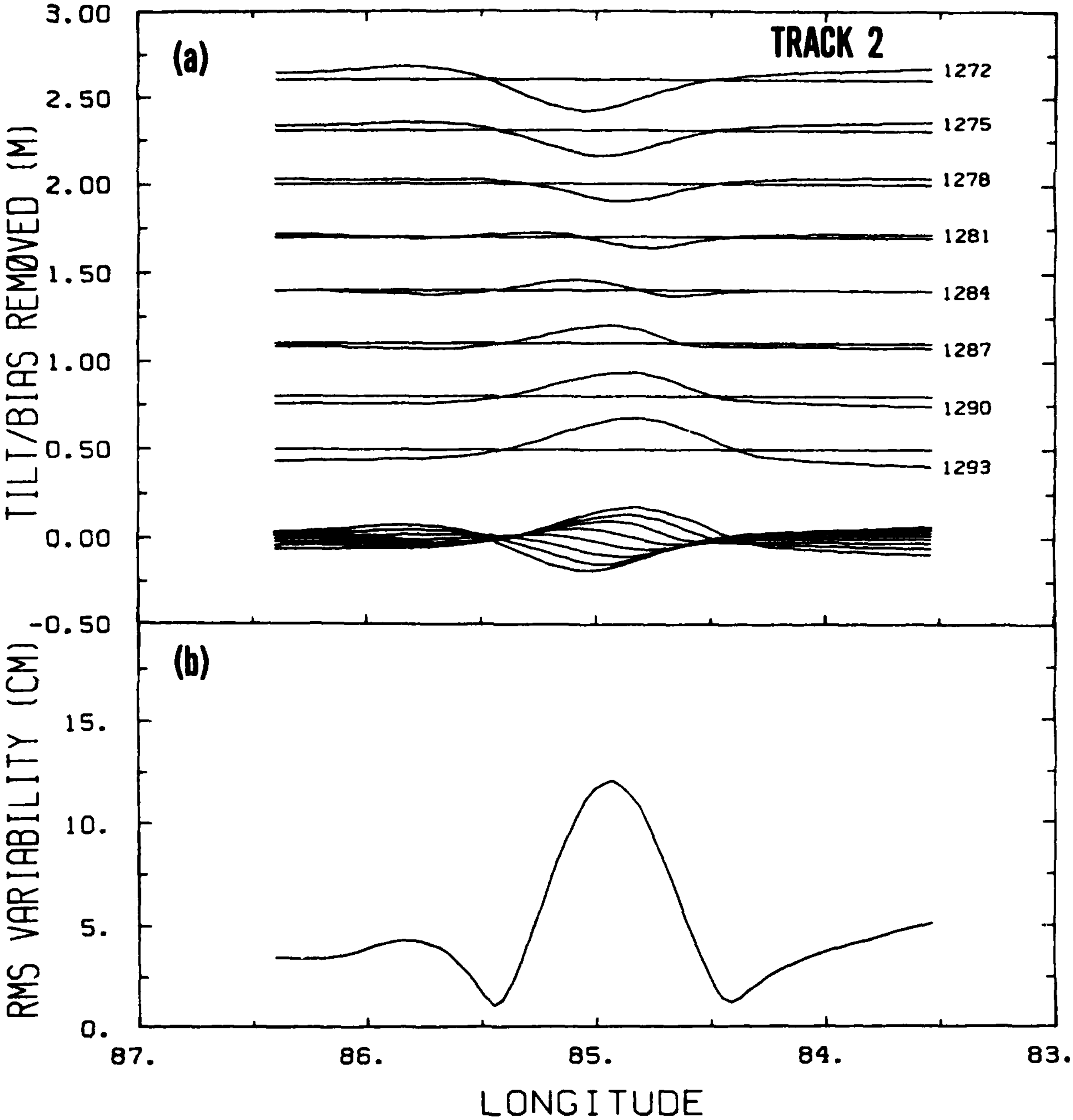
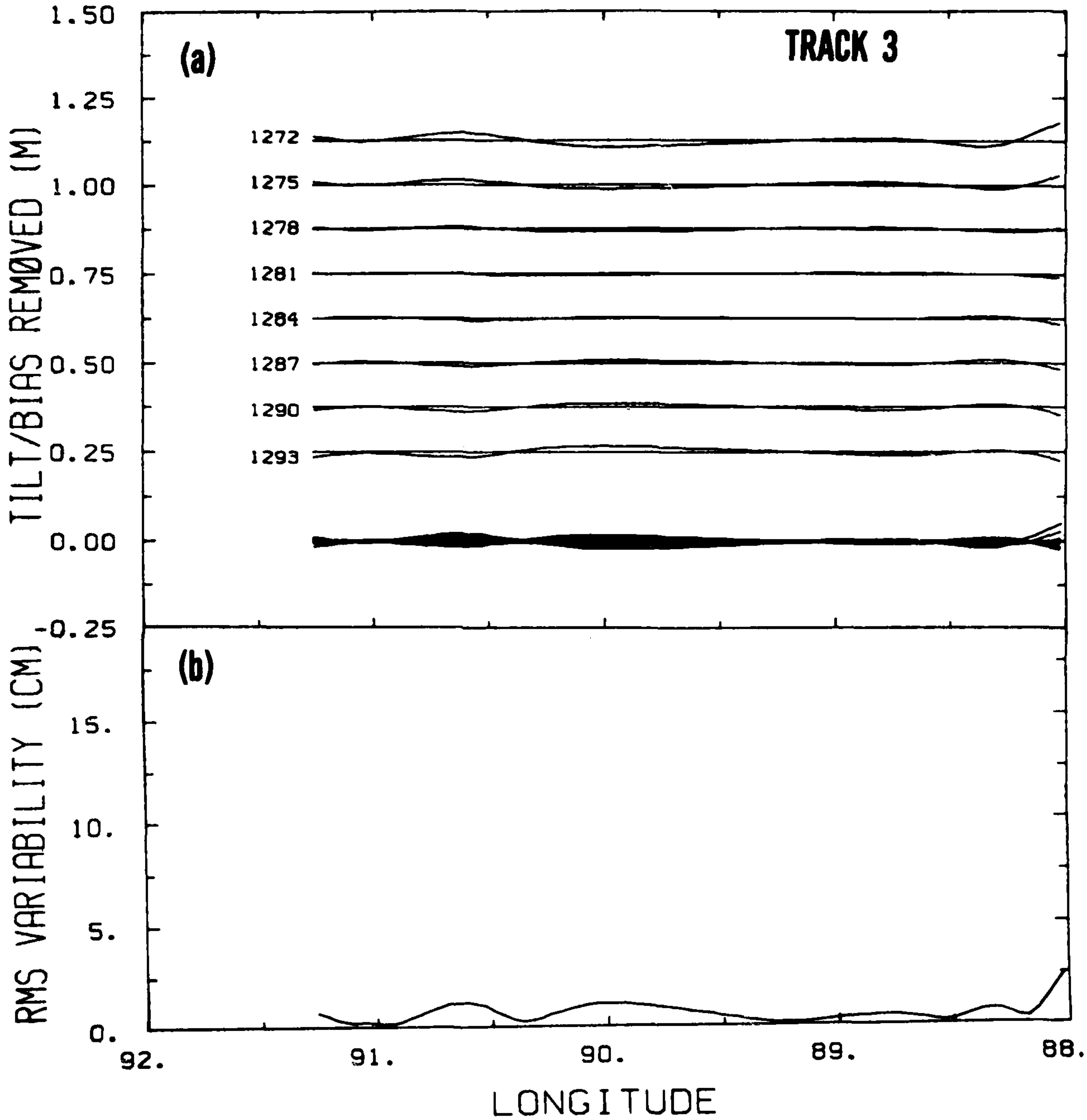

TRACK 2
(a)
(b)
1272
1275
1278
1281
1284
1287
1290
1293
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
TILT/BIAS REMØVED (M)
15.
10.
5.
0.
RMS VARIABILITY (CM)
87.
86.
85.
84.
83.
LONGITUDE

Fig. 5

FIGURE 6

Similar to Fig. 5 but for TRACK 3.



TRACK 3
(a)
(b)
TILT/BIAS REMØVED (M)
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
1272
1275
1278
1281
1284
1287
1290
1293
RMS VARIABILITY (CM)
15.
10.
5.
0.
92.
91.
90.
89.
88.
LONGITUDE

Fig. 6

FIGURE 7

Depth of the 22^{o}C isothermal surface along a line from the Yucatan Strait to Galveston obtained from NODC ship-of-opportunity XBT data for 12-13 August 1978. Also shown is the last surface position of the frontal boundary of the Loop Current as detected by GOES satellite infrared imagery (31 May). Location of the image from the synthetic aperture radar (SAR) is indicated by the rectangle.

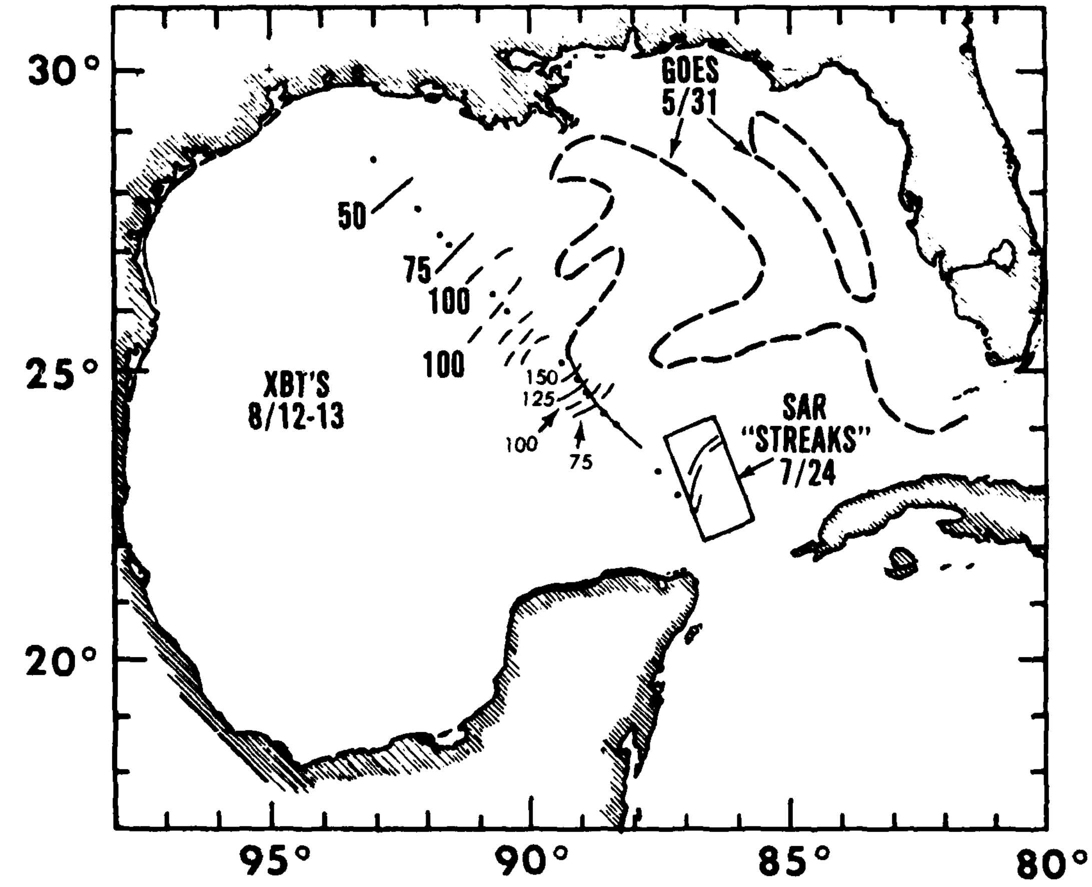

30°
25°
20°
95°
90°
85°
80°
GOES
5/31
50
75
100
100
XBT'S
8/12-13
150
125
100
75
SAR
"STREAKS"
7/24

Fig. 7

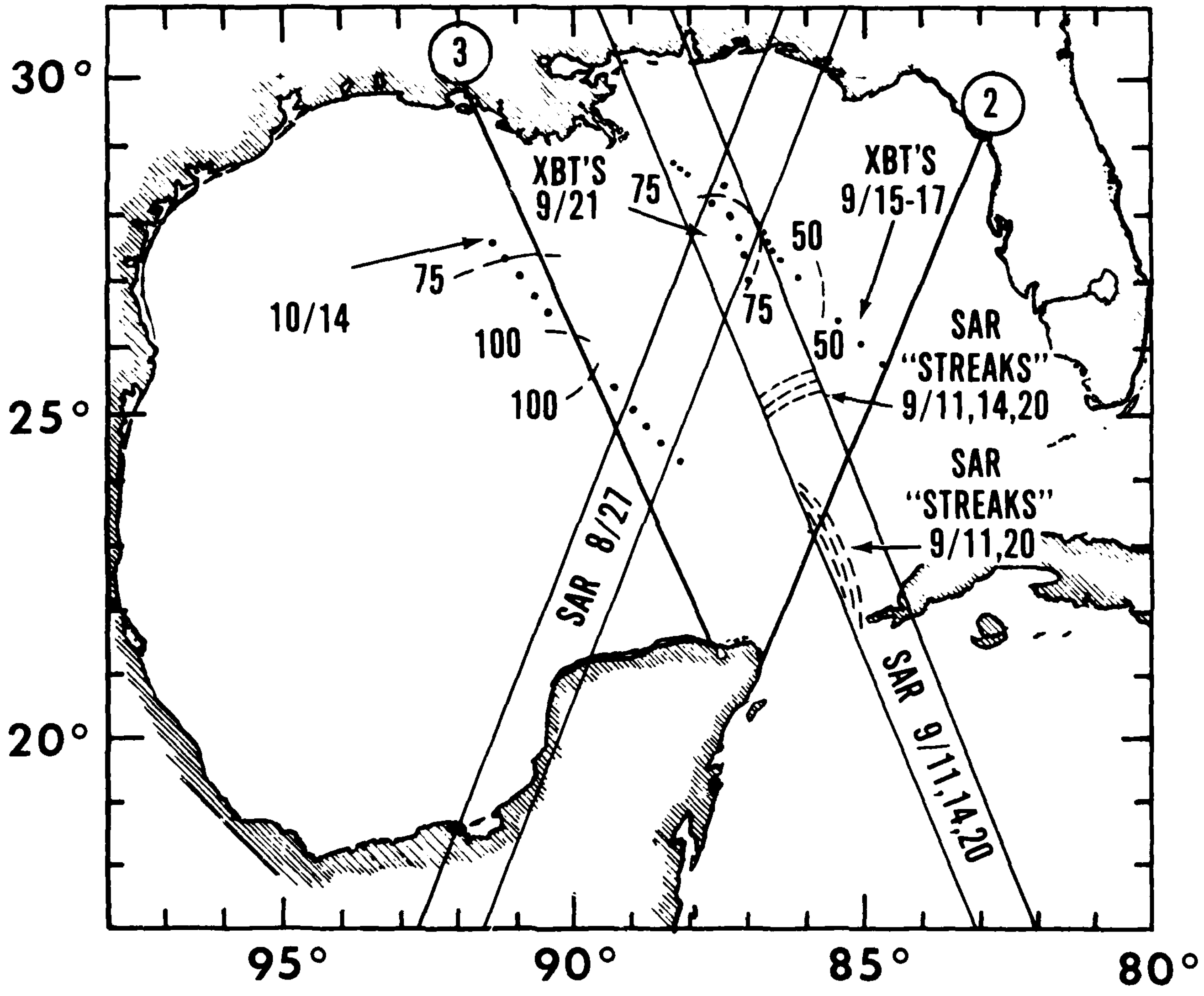
FIGURE 8

Optically processed synthetic aperture image (SAR) from Rev. 393, July 24, 1978 for the region shown by the box in Fig. 7. The Loop Current boundary is delineated by the SAR streaks. (See Fu and Holt, 1982).

Fig. 8

FIGURE 9

Depth of the 22 ^{o}C isothermal surface along XBT lines from measurements of 15-17 September, 21 September, and 14 October 1978. Also shown are the SEASAT ground tracks and the swaths mapped out by the synthetic radar (SAR) on board.



30°
25°
20°
95°
90°
85°
80°
3
2
XBT'S
9/21
XBT'S
9/15-17
10/14
75
100
100
75
75
50
50
75
SAR
"STREAKS"
9/11,14,20
SAR
"STREAKS"
9/11,20
SAR 8/27
SAR 9/11,14,20

Fig. 9

FIGURE 10

Depth of the 22^{o}C isothermal surface along two lines taken from XBT measurements on 26-27 October and 20-21 November 1978. Also shown is the first surface position of the frontal boundary of the Loop Current detected by GOES on 21 October following the summertime loss of the surface thermal gradient.

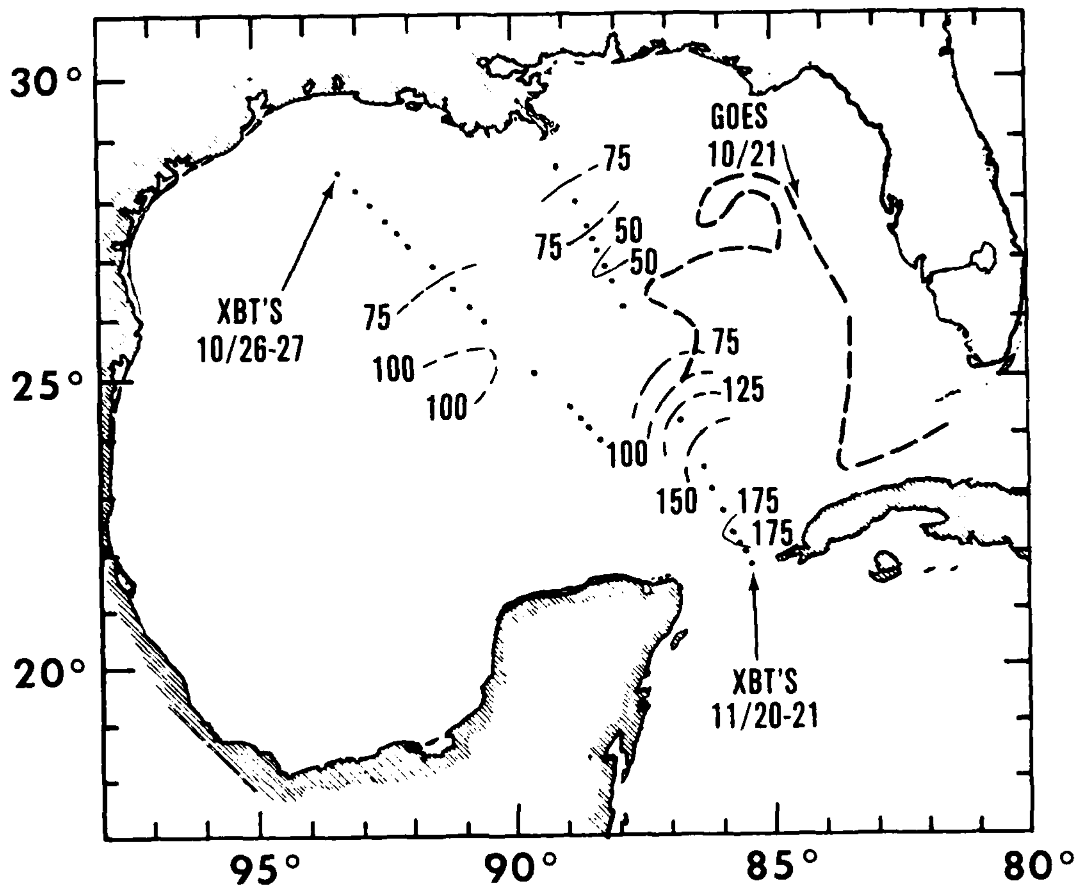

30°
25°
20°
95°
90°
85°
80°
GOES
10/21
XBT'S
10/26-27
XBT'S
11/20-21
75
75
50
50
75
75
100
100
125
100
150
175
175

Fig. 10

FIGURE 11

Position of the Loop Current boundary along a "wave-staff" extending from Cape San Antonio (extreme western Cuba) to the Mississippi Delta versus time in Julian days from 1 January 1976. Dots are the boundary positions obtained by the GOES sequence-analysis technique of Maul et al (1978). Multivalued distances indicate the existence of extreme Loop Current meanders or shed anticyclonie eddies. The solid line represents a nine-component Fourier recomposition (standard-deviation for five years ± 63 km) of 428 GOES observations of the Loop Current boundary which formed a randomly-spaced, gappy (in summer) time series.

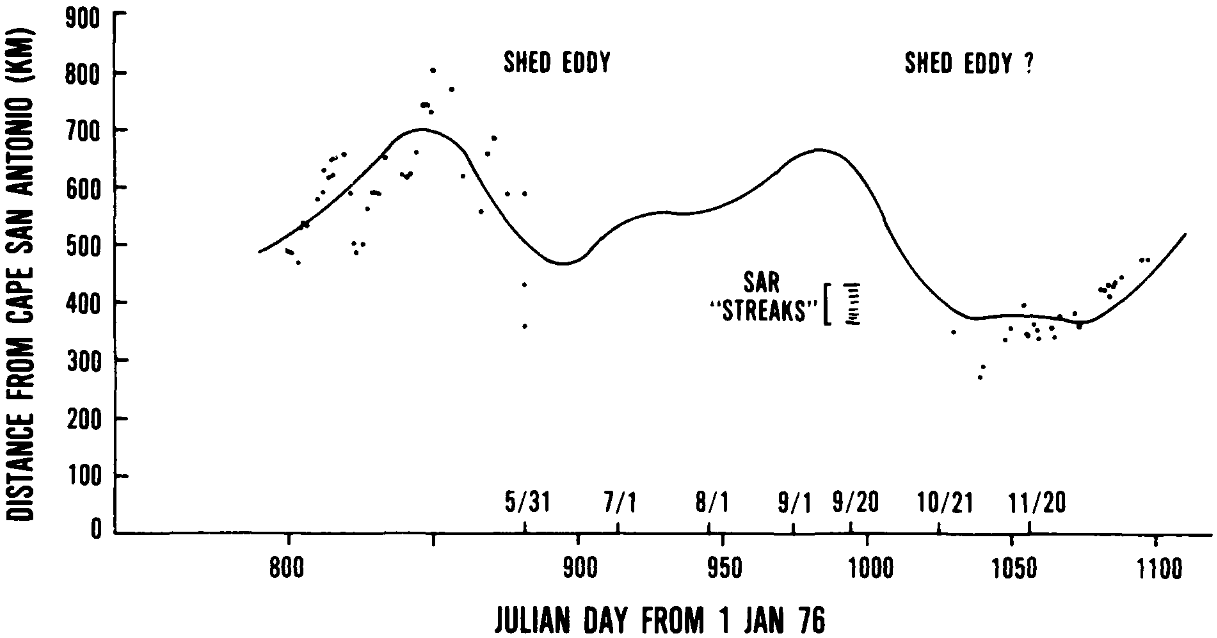

DISTANCE FROM CAPE SAN ANTONIO (KM)
900
800
700
600
500
400
300
200
100
0
SHED EDDY
SHED EDDY ?
SAR
"STREAKS"
5/31
7/1
8/1
9/1
9/20
10/21
11/20
800
900
950
1000
1050
1100
JULIAN DAY FROM 1 JAN 76

Fig. 11

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SEASAT

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

From 17 September to 10 October 1978 SEASAT made colinear passes over the Gulf of Mexico. Altimeter data for eight, three-day repeat passes over the eastern Gulf were examined using an arc-segment fitting technique to determine the mesoscale temporal variability of the sea surface. The pattern of sea height variability was then compared with sea height data generated by a numerical model of the Gulf (Hurlburt and Thompson, 1980) from the simulation of a complete cycle of Loop Current intrusion and shedding of an anticyclonic eddy. The

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model data was found to match that from the SEASAT altimeter when an anticyclonic eddy separated from the Loop Current and the Loop began to repenetrated into the eastern Gulf. Analysis of sparse ground truth data from ship-of-opportunity XBT's, satellite infrared imagery of the Loop Current boundary, and synthetic aperature radar (SAR) imagery, also from SEASAT, tend to confirm the circulation patterns deduced from the altimeter data and the numerical model.

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